

Proton-Proton Scattering from Standard to the Unknown with $\bar{\text{P}}\text{ANDA}$ @ HADES

Jana Rieger

Uppsala University



May 27
FAIRNESS 2022

*Knut and Alice
Wallenberg
Foundation*

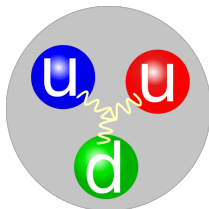


Swedish
Research
Council

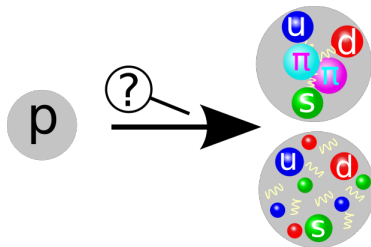
Outline

- 1 Motivation
- 2 pp @ 4.5 GeV Beam Time
- 3 The Standard – Elastic Scattering
- 4 The Unknown – Hyperon Form Factors
- 5 Conclusion

Hyperons vs. Nucleons

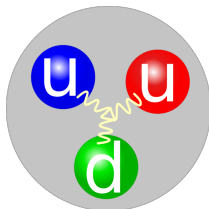


proton



Hyperons vs. Nucleons

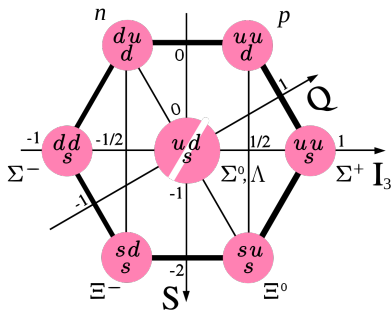
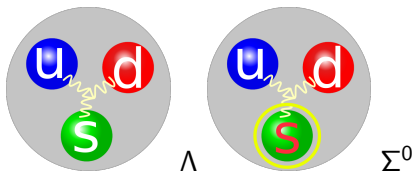
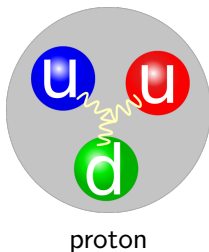
What if we add strangeness?



proton

Hyperons vs. Nucleons

What if we add strangeness?



Form Factors

Describe non-point-like character of particles,
dependent on four-momentum transfer q
→ Coupling of photon to hadron

Nucleon: Electron scattering

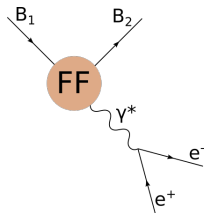
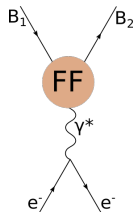
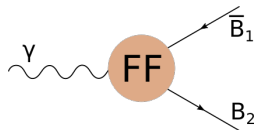
- Space-like ($q^2 < 0$) region
- Fixed target experiment

Challenge of **hyperons**: They are unstable!

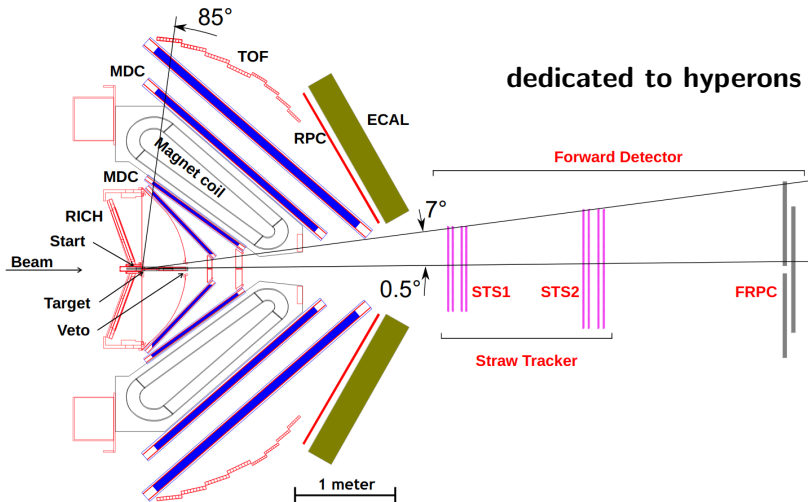
→ Study **Dalitz decay**

- Makes hyperon-hyperon TFF accessible
- Time-like ($q^2 > 0$) region

This has never been measured before!

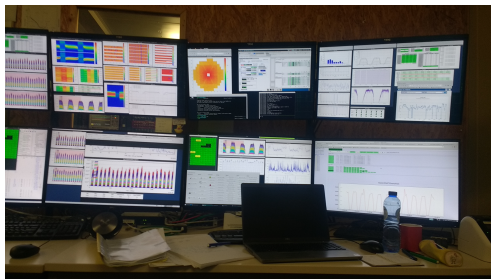


PANDA @HADES – Setup for pp @ 4.5 GeV Beam Time in Spring 2022



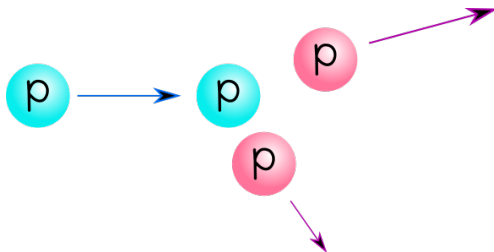
The HADES Feb22 Beam Time

- pp collisions at 4.5 GeV beam kinetic energy
- Hyperon campaign
see also talk by Konrad Sumara:
"Production and decays of hyperons in p+p reactions measured with HADES", Tuesday
- Total of 488.25 hours of data taking
- Total amount of data collected:
41 G Events (all triggers)
683973.7 GB



The Standard

– pp Elastic Scattering –



Many experiment parameters are still unknown but we know the physics...

pp Elastic Scattering

A well defined reaction

Kinematic relations

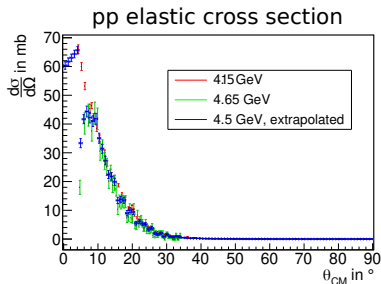
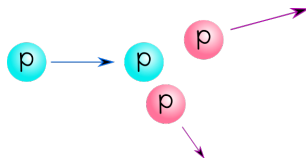
$$p = \frac{p_{\text{beam}}}{\cos \theta \cdot (1 + \tan^2 \theta \gamma_{\text{CM}}^2)}$$

$$\tan \theta_1 \cdot \tan \theta_2 = \frac{1}{\gamma_{\text{CM}}^2} = 0.29429$$

$$\varphi_2 = |180^\circ - \varphi_1|$$

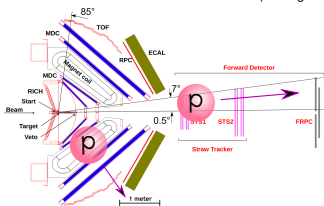
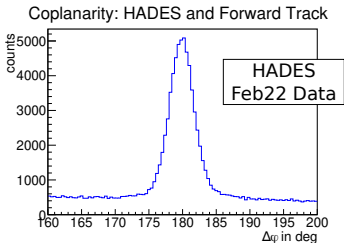
With a lot of existing data

from SAID database



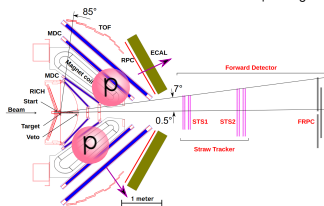
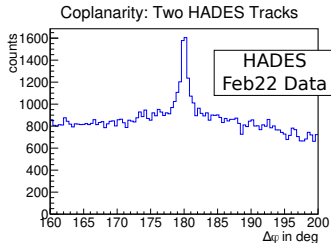
What can we learn from it?

- Online monitoring



Selection:

$$\tan \theta_1 \cdot \tan \theta_2 = 0.294 \pm 0.1$$

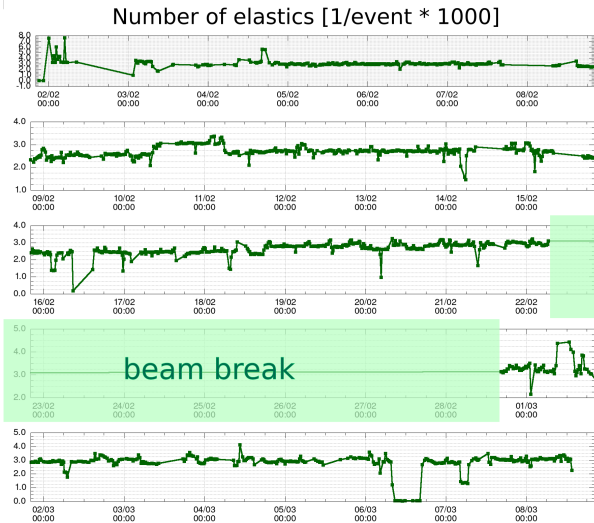


Selection:

$$\tan \theta_1 \cdot \tan \theta_2 = 0.294 \pm 0.015$$

What can we learn from it?

● Online monitoring



Selection on
 $\Delta\varphi$
 and
 $\tan\theta_1 \cdot \tan\theta_2$

Credits to
 Rafał Lalik
 and
 Konrad Sumara

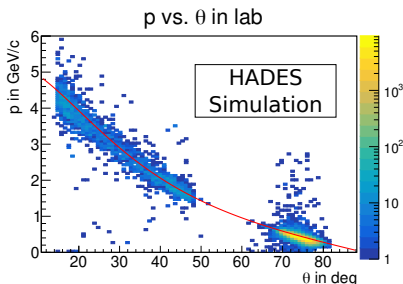
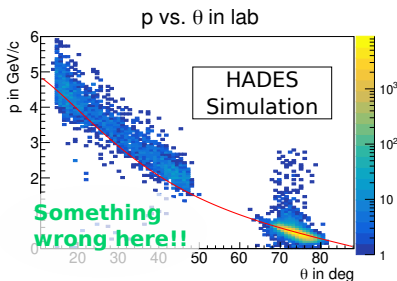
What can we learn from it?

- Online monitoring
- Calibration and quality assurance

see also talk by Gabriela Perez:

The new Forward Tracker System for the HADES FAIR Phase-0 experiment", Wednesday

From elastic scattering kinematics:
$$p = \frac{p_{\text{beam}}}{\cos \theta \cdot (1 + \tan^2 \theta \gamma_{\text{CM}}^2)}$$

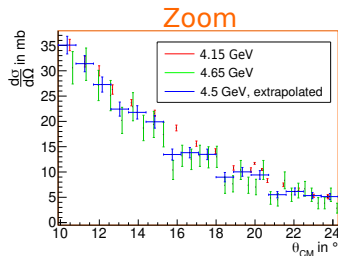
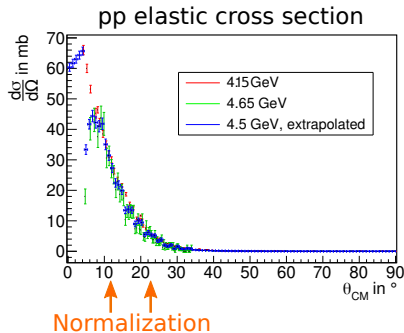
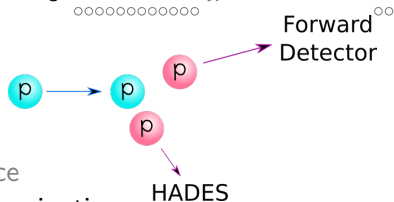


Corrected geometry

Elastic scattering, both protons detected

What can we learn from it?

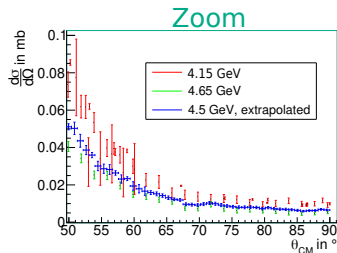
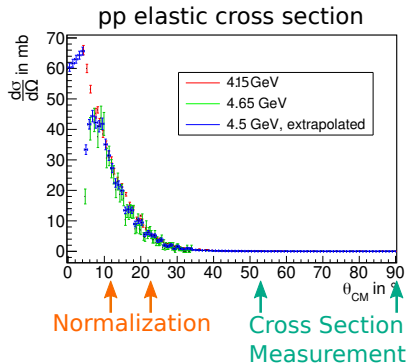
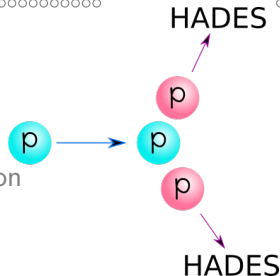
- Online monitoring
- Calibration and quality assurance
- Normalization – luminosity determination



Integrated cross section from $\theta_{CM} = 13^\circ - 22^\circ = 3.7^{+0.7}_{-0.3} \text{ mb}$

What can we learn from it?

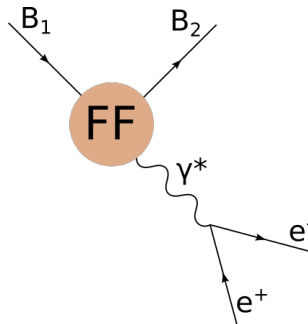
- Online monitoring
- Calibration and quality assurance
- Normalization – luminosity determination
- pp elastic cross section measurement



Integrated cross section from $\theta_{CM} = 55^\circ - 90^\circ = 0.04^{+0.02}_{-0.01}$ mb

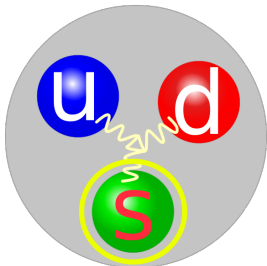
The Unknown

– Hyperon Form Factors –



Now the experiment is known and we can explore unknown physics ...

The Σ^0 Hyperon



$$\Sigma^0 \quad I(J^P) = 1(\frac{1}{2}^+)$$

Mass: $1193 \pm 0.024 \text{ MeV}$

Mean life: $(7.4 \pm 0.7) \cdot 10^{-20} \text{ s}$

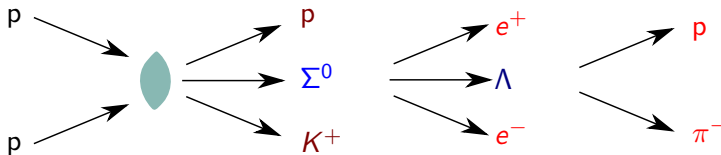
Decay mode	Branching ratio
$\Lambda \gamma$	100 %
$\Lambda \gamma \gamma$	< 3 %
$\Lambda e^+ e^-$	$5 \cdot 10^{-3}$ unmeasured

P.A. Zyla et al.(Particle Data Group), Prog. Theor. Exp. Phys.2020, 083C01 (2020)

Dalitz Decay – Challenges

- $\Sigma^0 - \Lambda$ mass difference (only 77 MeV)
 $\Rightarrow$ low dielectron ($e^+ e^-$) mass
- Large background from $\Sigma^0 \rightarrow \Lambda \gamma$

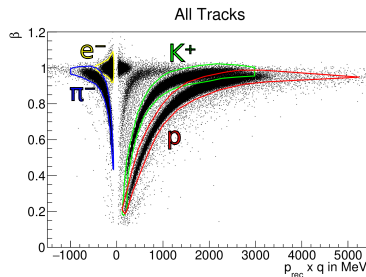
Simulation



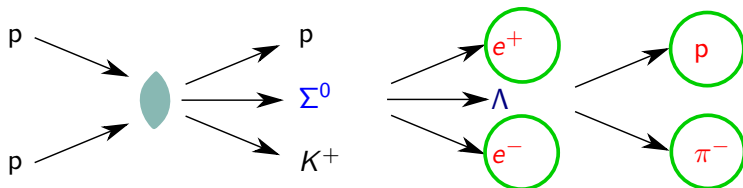
Simulated signal

- 1 000 000 events
- 4.5 GeV beam kinetic energy
- Uniform phase-space population

Particle identification



Reconstruction Strategy I



Simulated signal

- 1 000 000 events
- 4.5 GeV beam kinetic energy $\hat{=}$ $\sqrt{s} = 3.5$ GeV

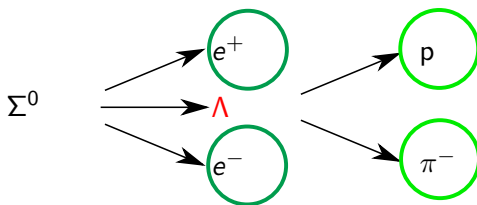
Analysis Strategy I

Inclusive reconstruction of $\Sigma^0 \rightarrow \Lambda e^+ e^-$

○ Reconstructed particles

Strategy I: Λ Reconstruction

Vertex fit in secondary vertex



- Λ production vertex from e^+ and e^-
- Λ decay vertex from p and π^-
- Λ direction is given by vertex positions
- Kinematic fit ensures 4-momentum conservation in secondary vertex to reconstruct Λ momentum

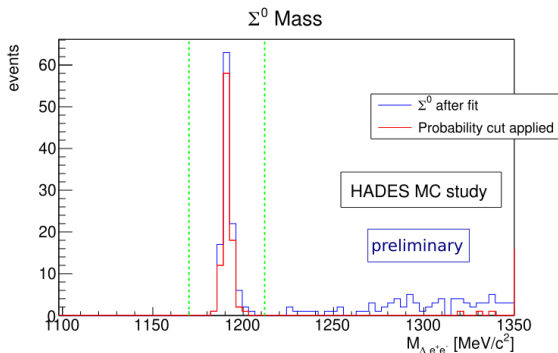
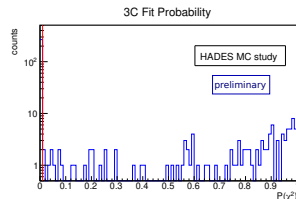
Kinematic fitting software developed in Uppsala

Strategy I: Σ^0 Reconstruction

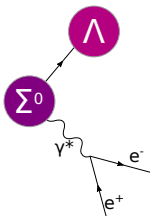
Finally: Build Σ^0 from $\Lambda e^+ e^-$

Selection:

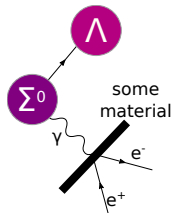
- $P(\chi^2) > 1\%$
- $1170 \text{ MeV}/c^2 < m_\Sigma < 1216 \text{ MeV}/c^2$



Strategy I: Σ^0 Radiative Decay as Background Source



Dalitz decay:



Photon conversion:

$$pp \rightarrow pK^+\Sigma^0[\Lambda\gamma]$$

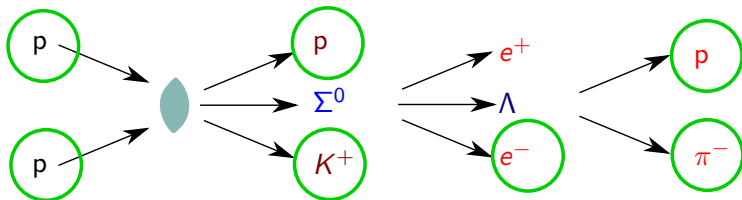
- Cross section $pp \rightarrow pK^+\Sigma^0$: $23.5 \mu b$

V. Flaminio, et al., (1984), eprint: CERN-HERA-84-01

- Fraction that passes the Σ^0 Dalitz selection criteria: $5 \cdot 10^{-8}$ (1 of 20 million)
- Corresponding $S/\sqrt{S+B}$: 9.1

Very good background suppression by kinematic fit

Reconstruction Strategy II



Simulated signal

- 1 000 000 events
- 4.5 GeV beam kinetic energy $\hat{=}$ $\sqrt{s} = 3.5$ GeV

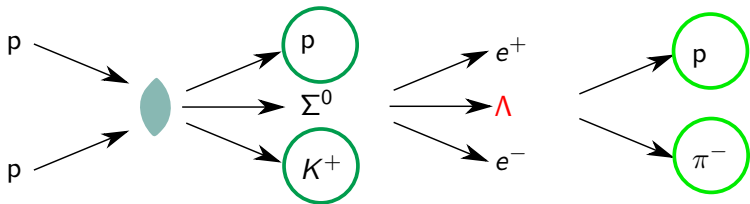
Analysis Strategy II

(almost) Exclusive reconstruction of $pp \rightarrow pK^+\Sigma^0[\Lambda e^+e^-]$,
 e^+ constructed by kinematic fitting

○ Reconstructed particles

Strategy II: Λ Reconstruction

Vertex fit in secondary vertex

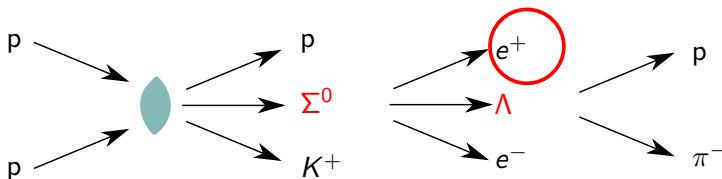


- Σ^0 decays in **interaction point**, Λ in **secondary vertex**
- Find two vertices from $p\pi^-$ and pK^+
- Λ direction is given by vertex positions
- Kinematic fit in secondary vertex to reconstruct Λ momentum

Kinematic fitting software developed in Uppsala

Strategy II: e^+ Reconstruction

Get e^+ from $pK^+\Lambda e^-$ missing 4-momentum



- Initial 4-momentum is known
- Λ candidate from vertex fit
- p , K^+ and e^- measured
- Determine e^+ momentum by kinematic fit

○ Missing particle

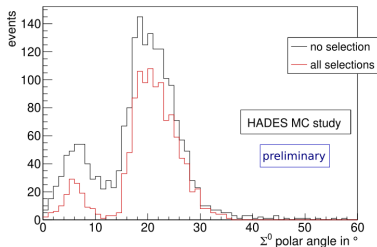
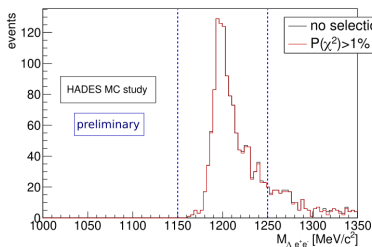
Kinematic fitting software developed in Uppsala

Strategy II: Σ^0 Reconstruction

Finally: Build Σ^0 from $\Lambda e^+ e^-$

Selection criteria:

- $P(\chi^2) > 1\%$
- $1150 \text{ MeV}/c^2 < m_{\Sigma} < 1250 \text{ MeV}/c^2$



Strategy II: Most Prominent BG: Σ^0 Radiative Decay

$$pp \rightarrow pK^+\Sigma^0[\Lambda\gamma]$$

- Cross section $pp \rightarrow pK^+\Sigma^0$: $23.5 \mu b$

V. Flaminio, et al., (1984), eprint: CERN-HERA-84-01

- Fraction that passes the Σ^0 Dalitz selection criteria: $4.5 \cdot 10^{-5}$ (886 of 20 million)
- Corresponding $S/\sqrt{S+B}$: 11.5
- Phase space largely overlapping

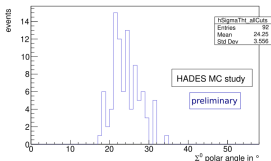
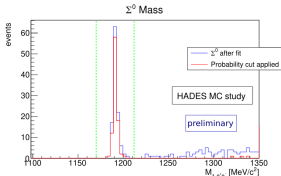
Apply additional background suppression selections

- Electron production vertex and hit structure
- **Signal:** -18 %; **BG:** -76 %
- New $S/\sqrt{S+B}$: 17

Strategy I and II

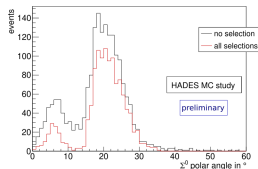
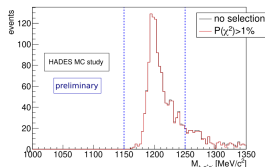
Strategy I

- Detected particles:
 e^-, e^+, p, π^-
- Very good background supp.:
 $\frac{S}{\sqrt{S+B}} = 9.1, \frac{S}{B} = 92$
- Counts/day: 15



Strategy II

- Detected particles:
 p, K^+, e^-, p, π^-
- More signal, more background:
 $\frac{S}{\sqrt{S+B}} = 17, \frac{S}{B} = 0.48$
- Counts/day: 152



Conclusion

At First: The standard, elastic scattering

- Understand the data
- Calibrate the data
- Normalize the data
- Analyze the data

Then: The unknown, Σ^0 Dalitz decay

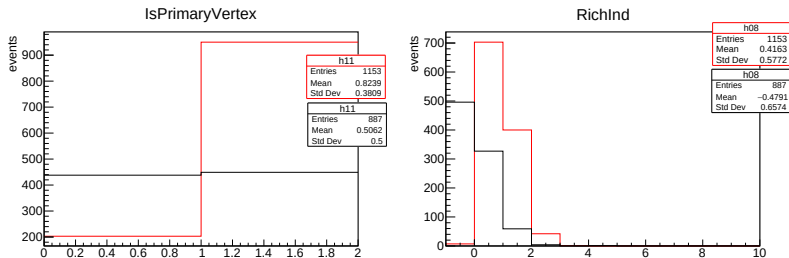
- Do analysis on Feb22 beam time data
- Measure the Σ^0 Dalitz decay!



BACKUP

Strategy I: Most Prominent BG: Σ^0 Radiative Decay

Find background suppression criteria



Cut on RICH index ≥ 0 and isPrimaryVertex == 1

Signal: 1153 $\rightarrow$ 947; **BG:** 886 $\rightarrow$ 209

New S/B: 0.477

Expected Count Rates

- Luminosity $\mathcal{L} = 1.5 \cdot 10^{31} \text{ cm}^{-2}\text{s}^{-1}$ (beam time proposal)
- Cross section $\sigma(pp \rightarrow pK^+\Sigma^0) = 23.5 \mu\text{b}$
- Branching ratio $\text{BR}(\Sigma^0 \rightarrow \Lambda e^+ e^-) = 5 \cdot 10^{-3}$
- Efficiency and Acceptance ($\epsilon \cdot A \cdot \text{BR}(\Lambda \rightarrow p\pi^-)$)
 $= 9.968 \cdot 10^{-4}$ (exclusive $pp \rightarrow pK^+\Sigma^0[\rightarrow \Lambda e^+ e^-]$)
 $= 9.684 \cdot 10^{-5}$ (inclusive $\Sigma^0 \rightarrow \Lambda e^+ e^-$)

$$pp \rightarrow pK^+\Sigma^0[\rightarrow \Lambda(e^+)e^-]/\text{day}$$

$$N_{\text{LH}} = \mathcal{L} \cdot \sigma \cdot \text{BR} \cdot (\epsilon A) \cdot t \approx 152$$

$$\Sigma^0 \rightarrow \Lambda e^+ e^-/\text{day}$$

$$N_{\text{LH}} = \mathcal{L} \cdot \sigma \cdot \text{BR} \cdot (\epsilon A) \cdot t \approx 15$$

Kinematic Fitter for HADES Software

Suppose there are N measured and M unmeasured variables related by K constraints

$$f_k(\eta_1, \eta_2, \dots, \eta_N, \xi_1, \xi_2, \dots, \xi_M) = 0. \quad (1)$$

Goal: Minimize $\chi^2(\eta) = (y - \eta)^T V(y)(y - \eta)$ under those K constraints

Procedure: Introduce Lagrangian Multipliers λ

$$\chi^2(\eta, \xi, \lambda) = (y - \eta)^T V(y)(y - \eta) + 2\lambda^T f(\eta, \xi) = \text{minimum} \quad (2)$$

y : Measurements, $V(y)$: Covariance matrix of y

4C Fitter

Constraint equations for N particles:

$$f_1 = \sum_{n=1}^N p_n \cdot \sin \vartheta_n \cos \varphi_n - p_{x_{\text{ini}}} = 0$$

$$f_2 = \sum_{n=1}^N p_n \cdot \sin \vartheta_n \sin \varphi_n - p_{y_{\text{ini}}} = 0$$

$$f_3 = \sum_{n=1}^N p_n \cdot \cos \vartheta_n - p_{z_{\text{ini}}} = 0$$

$$f_4 = \sum_{n=1}^N \sqrt{p_n^2 + m_n^2} - E_{\text{ini}} = 0$$

The Fitting Procedure – Minimization

χ^2 minimization will result in $N + M + K$ equations:

$$\nabla_{\eta} \chi^2 = -2V^{-1}(y - \eta) + 2F_{\eta}^T \lambda = 0$$

$$\nabla_{\xi} \chi^2 = 2F_{\xi}^T \lambda = 0$$

$$\nabla_{\lambda} \chi^2 = 2f(\eta, \xi) = 0$$

where F_{η} and F_{ξ} are defined by

$$(F_{\eta})_{ij} = \frac{\partial f_i}{\partial \eta_j}, \quad (F_{\xi})_{ij} = \frac{\partial f_i}{\partial \xi_j} \quad (3)$$

→Solve in iterative procedure